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Effect of Vertically Travelling Fires on the Collapse of Tall Buildings

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Abstract

Many previous tall building fires demonstrate that despite code compliant construction fires often spread vertically and burn over multiple floors at the same time. The collapses of the WTC complex buildings in 9/11 as well as other partial collapses like the ones of the Windsor Tower in Madrid and of the Technical University of Delft building posed new questions on the stability of tall buildings in fire. These accidents have shown that local or global collapse is possible in multi-floor fires. In most of the previous work involving multi-floor fires all floors were assumed to be heated simultaneously although in reality fires travel from one floor to another. This paper extends previous research by focusing on the collapse mechanisms of tall buildings in fire and performs a parametric study using various travelling rates. The results of the study demonstrate that vertically travelling fires have beneficial impact in terms of the global structural response of tall buildings in comparison to simultaneous fires. Contrary to the beneficial effect of the travelling fires in terms of the global structural response, it was noticed that higher tensile forces were also present in the floors compared to simultaneous multi-floor case. Designers are therefore advised to consider simultaneous multi-floor fire as an upper bound scenario. However, a scenario where a travelling fire is used is also suggested to be examined, as the tensile capacity of connections may be underestimated.

Keywords: Vertically travelling fires, Structural fire resistance, Performance based structural engineering, Tall building collapse

1. Introduction

Structural fire resistance design is based on active and passive methods of fire protection and is usually applied in a prescriptive manner but increasingly performance based engineering approaches are being adopted, especially for large and complex projects (Lamont et al., 2006). Fire in tall buildings present the particularly unique challenge of ensuring safety of potentially very large numbers of occupants in the face of long emergency response times because of location (busy city centres) and building height. Furthermore, many previous tall building fires demonstrate that despite code compliant construction (designed to contain fires in the compartment of origin) fires often spread vertically and burn over multiple floors at the same time. Tall buildings are often also complex and innovative in terms of structural form and contain spatial configurations involving large open spaces and high atria and column heights etc.

A performance based approach should include structural fire resistance as an integral part of the fire safety strategy since relying entirely on active protection measures presents many uncertainties, such as: in actual evacuation times or the non-activation of sprinklers due to malfunction (Parque Centrale, Moncada et al., 2005); damage by earthquake (Northridge earthquake, Scawthorn et al., 1998);

or because the building is under construction (Mandarin hotel, large projects are sometimes under construction for years). NIST (NIST, 2007) suggests that tall buildings should be designed to resist the worst possible fires without taking sprinklers into account. By contrast the performance of passive protection measures, such as the inherent fire resistance of the structure, can be more reliably predicted and offers redundancy for robustness.

The collapses of the WTC complex buildings in 9/11 as well as other partial collapses like the ones of the Windsor Tower in Madrid and of the Technical University of Delft building posed new questions on the stability of tall buildings in fire. These accidents have shown that local or global collapse is possible in multifloor fires. Tall building collapse under multifloor fires has thus attracted the interest of researchers at the University of Edinburgh for more than a decade (Usmani et al., 2003; Usmani, 2005; Usmani et al., 2009; Flint et al., 2007) since this is not an unusual scenario despite being usually ignored in practice. However first example of such a scenario in UK was introduced recently in the 200 m high Heron Tower in London by ARUP's fire consultants considering the case of a simultaneous three floor fire. Other researchers have also examined the collapse of structures in case of other type of fires such as localised ones. Recently, Fang et al. proposed a robustness assessment design framework that was involving a temperature-dependent approach (TDA) and a temperature-independent approach (TIA) for composite structures subjected to localised fires. Sun et al. recently also presented a procedure that has been imple-

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mented into the VULCAN software in order to perform progressive collapse analysis of steel structures in fire.

In most of the previous work all floors were assumed to be heated simultaneously although in reality fires travel from one floor to another. Previous research considering vertical travelling fires is very limited. Recently, Roben et al. (2010) examined the behaviour of structures during a vertically travelling fire scenario, however their member selection was based on the assumption that a global collapse will not occur and all the members will cool down to ambient. Their research indicated that possible connection failure may take place because of cyclic column movements. As the phenomenon of vertical fire spread in high-rise buildings is complex and out of the scope of this work, a simple time delay is used to simulate the beginning of heating on each successive floor. It is expected that this approach will be adequate to study the key structural effects of vertically travelling fires. The mechanisms of fire spread from one floor to another are however discussed and a range of time delays are considered for the parametric studies.

2. Structural and Fire Modelling

All the structural and heat transfer analyses that are presented in this paper were constructed using the open-source and object-oriented structural engineering software framework OpenSees (McKenna, 1997). OpenSees is effectively a library of advanced computational tools for the nonlinear analysis of structures. The OpenSees framework is being extended at the University of Edinburgh by adding classes that introduce into OpenSees the capability of performing analyses of structures in fire including both heat transfer and thermo-mechanical analysis (Usmani et al., 2010). All the new developments have been validated and are to be included in the future general release of OpenSees (by PEER and UC Berkeley) so that any interested engineer or researcher can examine and criticise this work and use the software freely for consulting or research purposes. The modelling scripts used for this study will be accessible in public domain at the University of Edinburgh OpenSees wiki site which hosts the newly developed source code as well as detailed documentations so anyone can reproduce the results presented in this paper. Consequently this paper is also a platform for presenting OpenSees fire capabilities of efficient structural fire modelling by integrating the fire, heat transfer and structural modules into one analysis framework.

2.1. Structural modelling

2.1.1. Finite element model

The structural model is identical to that of a previous study performed by the authors. The reason for performing this parametric study on the same structural model is to enable comparisons with the collapse mechanisms ob-

served using a simultaneous fire assumption in previous research and vertically travelling fires examined in this paper. The structural layout can be seen in Fig. 4. The 2D finite element model is based on a 2D slice along the longest span over 12 storeys of a generic composite steel frame tall building constructed using universal beams and columns. Although a two-dimensional representation can not take into account load redistribution in the third dimension, previous research comparing two and three dimensional models by Flint (2005) and Quiel and Garlock (2010) have demonstrated that a two dimensional model can reasonably predict the performance of a perimeter column-floor interaction system in fire. This is primarily because of the assumption of uniform temperature in the whole compartment in a flashover fire. Three dimensional effects have also been examined for a similar building layout (Kotsovinos, 2013), and the two dimensional model has been compared against a three dimensional grillage model (Fig. 1). The results showed that the two-dimensional model can predict well the horizontal displacement (and thus also membrane forces) at the column-floor connection but it overestimated the midspan deflection as seen in Figs. 2 and 3 which shows the plots of horizontal displacements (at the floor-column connection) and floor midspan deflections for the scenarios considered (Kotsovinos, 2013). These scenarios were a single floor 'short hot' fire and a 'long cool' parametric fire.

For the analyses performed in this paper the building will be assumed to have a fixed beam-column connection at the column end. This assumption implies that transla-

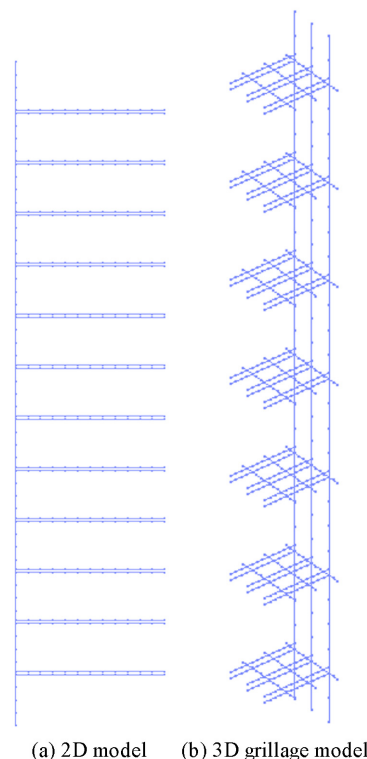


Figure 1. Finite element models.

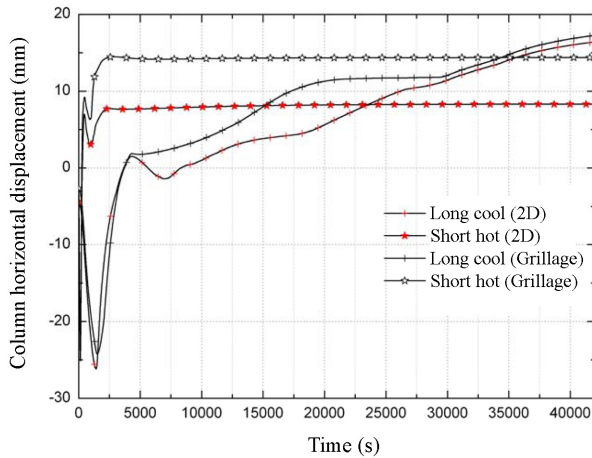


Figure 2. Comparison of column horizontal displacement.

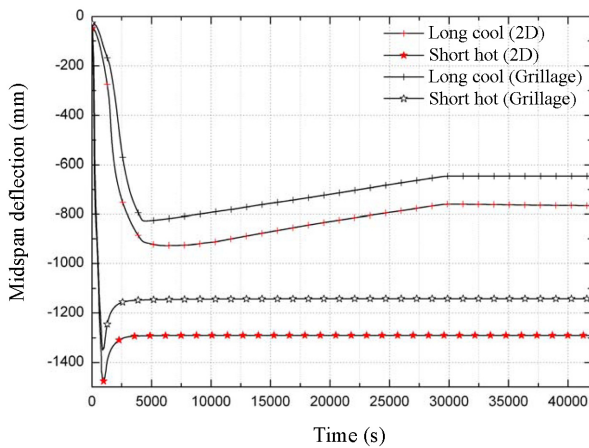


Figure 3. Comparison of floor midspan deflection.

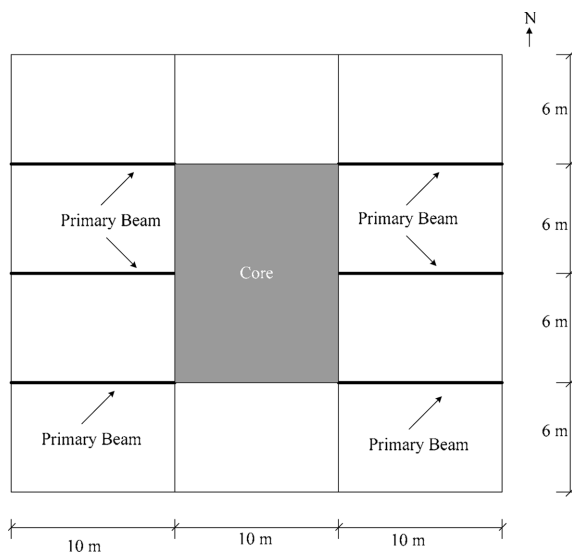


Figure 4. Structural layout.

joining the two members are constrained to be identical. As a result connection failure is not taken into account in this study. At the rigid core end the steel beam and the slab (forming the composite floor) are both pinned to a rigid lateral restraint. This connection also simulates a fixed-end connection for the composite floor.

2.1.2. Elements

For this study distributed plasticity displacement-based beam-column elements (*dispBeamColumn2DThermal*) are used for modelling the structural members (columns, beams and slabs). Five integration points are used along the length of the element where each integration point represents a *fiberSection*. For each *fiberSection* a sufficiently high number of fibres are used to obtain a desired level of accuracy in modelling the cross-sectional stress states. Hence, these elements allow monitoring plasticity through the depth of the section along the whole length of the element. Monitoring plastic hinges becomes possible by either recording the moments at a particular location or by calculating the plastic rotation. A co-rotational transformation was selected to account for large displacements, including P-Δ effect (the usually refers to moments induced in the column because of building sway but here we mean moments induced in the column due to floor lateral displacements induced by the thermal actions). A sufficient number of elements is used to capture the member nonlinear behaviour such as p-δ type effects (resulting from the interaction between the axial force and bending moments in the composite beams representing the floor slab).

The composite floor composed of the steel beam and the concrete slab is modelled using separate *dispBeamColumn2DThermal* elements for the beam and the slab. This implies that crack formation or any loss of composite action between concrete slab and steel beam are not taken into account. The full shear interaction is idealised by connecting each set of corresponding nodes of the slab and beam elements with a *rigidLink* constraint which tie the translation and rotational degrees of freedom of the slab to follow that of the beam.

2.1.3. Materials

Materials taking into account all the nonlinear characteristics were used. For the steel members (columns and beams) a yield strength of 300 N/mm² and modulus of elasticity of 210 GPa were assumed. The concrete slab was assumed to have a compressive strength of 30 N/mm² and a tensile strength of 5% of its compressive strength. The material constitutive model adopted is a modified Kent and Park model (Kent et al., 1969; Scott et al., 1982). The steel reinforcement was assumed to have yield strength of 475 N/mm². The material properties under elevated temperatures are varied in OpenSees according to the values given by Eurocode 2 (2004). Since this paper is investigating vertically travelling fires, this implies that

tions and rotations of the beam and column at the node

floors will not be heating simultaneously and hence a floor may cool down while another floor is heated. Thus the material classes were modified appropriately in OpenSees to take into account the cooling stage of fire. Steel is considered in this paper to regain its stiffness and strength when cooled down to ambient temperature. Thermal strain is also reversible during cooling. These are usual assumptions when performing structural fire analysis of steel structures. There is a lack of experimental data that could be used to establish a reliable stress strain curve of concrete in cooling (Khoury, 2000; Fletcher et al., 2007). The compressive strength, strain corresponding to compressive strength and ultimate (crushing) strain of concrete do not recover during cooling. These properties were allowed to change in a cooling scenario according to EN 1994-1-2:2005 (Eurocode 4, 2005). The main hypothesis of EN 1994-1-2 is that the concrete strain corresponding to the compressive strength will be fixed during the whole cooling phase and equal to the value that was reached at the maximum temperature of the heating phase. Then based on the compressive strength and the corresponding strain, the elastic modulus can be calculated. Thermal strains during the cooling phase are assumed to be reversible. This is a commonly used assumption. This assumption has been questioned by previous researchers for temperatures over 600°C (Schneider, 1988) due to material cracking. However, the validity of this assumption is not important for this paper since concrete temperatures do not get so high and concrete cooling response does not dominate the structural behaviour. Clearly more research is required in this area when modelling concrete structures under very high temperatures.

2.1.4. Collapse modelling process

Gravity loading is first applied using a quasi-static analysis procedure. Then the “time” is set back to zero and the structural fire analysis is performed on the model. An implicit dynamic procedure is used for performing progressive collapse analysis. Quasi-static integration

methods like load control have significant limitations in dealing with local or global instabilities that commonly occur in modelling structures subjected to fire (because of the stresses generated by restraining thermal deformations). The numerical scheme selected for the dynamic analysis is an implicit solution with a Hilber-Hughes-Taylor integrator with $\alpha = 0.7$ to add numerical damping to the model (Hilber et al., 1977). This procedure has been shown from previous studies to be able to model progressive collapse effectively.

2.2. Fire and heat transfer modelling

2.2.1. Representation of vertically travelling fires

Multifloor floor fires in high-rise buildings can be associated with a variety of factors. Generally speaking, there are three possible mechanisms that enable fire to travel from one floor to an adjacent floor (SFPE, 2012). It can travel upwards by compromising the perimeter fire barrier materials between the floor slab and curtains walls, or by igniting the interior vertical ductwork through floors. Secondly, external burning, which is associated with most fully developed compartment fires, could ignite combustibles in the upper floors by radiation heat transfer through glazing or by direct flame impingement through other openings. Finally, external flaming could also ignite external insulation material which could then involve many floors on fire even more rapidly, as witnessed in the 28 storey high building in Shanghai.

Modelling the process of vertical fire spread can be complicated by a number of factors, such as the geometry of the façade, the shape of the opening (Drysdale, 1998), the fire resistance of the glazing, the ambient atmosphere and the type of occupancy. However, the problem can be simplified for structural fire analysis by recognizing that post-flashover fires can develop at different time intervals for different floors. Therefore, a simple yet important parameter, time delay (Δt_{delay}), has been introduced to study the structural performances in vertical travelling fires (Usmani et al., 2009).

In this work, it is assumed that the fire travels upward

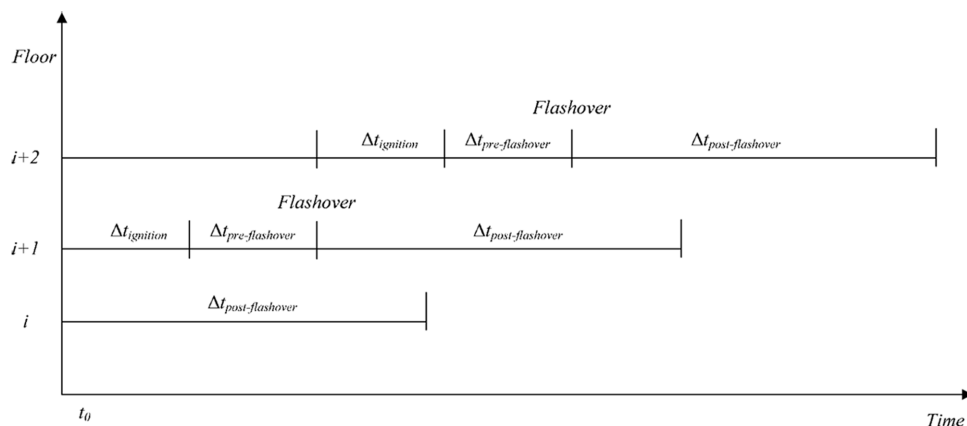


Figure 5. Time sequence of the vertically travelling fire over multiple floors.

progressively from one floor to the other, with vertical projection of the external flame not exceeding the most adjacent upper floor. The fire load and ventilation condition for each of the floors are identical. A constant time delay Δt_{delay} is assigned to each floor once post-flashover fire has developed in its adjacent downward floor, with

$$\Delta t_{delay} = \Delta t_{ignition} + \Delta t_{pre-flashover} \quad (1)$$

where $\Delta t_{ignition}$ is the time interval between the time of flashover in the floor below and the time of ignition at the current floor and $\Delta t_{pre-flashover}$ is the time taken from ignition to flashover at the current floor.

The time sequence of fire development at different floors is indicated in Fig. 5. It is assumed that the post-flashover fire starts at the initial time t_0 at the i^{th} floor. The first component of Δt_{delay} , $\Delta t_{ignition}$, is associated with the fire spread from one floor to the other, and can vary greatly with these factors discussed at the beginning of this section. The values of $\Delta t_{ignition}$ are varied from 500 to 900 s in the current work. The second component $\Delta t_{pre-flashover}$ is associated with the occurrence of flashover in compartment fires. Flashover can be interpreted as a case of thermal instability within the fire compartment which is dependant on the ventilation conditions and the thermal properties of the compartment boundaries (Drysdale, 1998). It was however suggested that it is difficult to predict the time to flashover due to the dependency on random variations of some factors during the very early stage of compartment fires (Drysdale, 1998). Reported values of time to flashover ($\Delta t_{pre-flashover}$) vary from 100 to 1600 s (Drysdale, 1998; Lai et al., 2009). Therefore, Δt_{delay} is selected here in the range of 600–2500 s for the purpose of parametric studies. Shorter time delays correspond to faster travelling fires while longer ones for slower travelling fires.

The post-flashover fires for each floor are represented by parametric fires as given in EC1 (EN1991-1-2, 2002). The fire load density is chosen to be 420.0 MJ/m² for typical office buildings according to (EN1991-1-2, 2002). The compartment has a floor area of 240 m² and an opening factor of 0.07. The lining material is assumed to be light weight concrete, corresponding to the thermal inertia of 1159 J/m²s^{0.5}K. It is also assumed that the fire growth rate is medium, which gives the shortest possible duration of heating phase $t_{lim} = 20$ min according to EC1 (EN1991-1-2, 2002). By applying these values, the temperature-time curve is obtained as shown in Fig. 6.

2.2.2. Heat transfer modelling

In the current work, the steel beams are assumed to be unprotected. This is a conservative assumption based on a worst case design approach or deliberate omission of beam fire protection as part of a performance-based engineering approach (Lamont et al., 2006). This could also imply possible previous damage that occurred during an

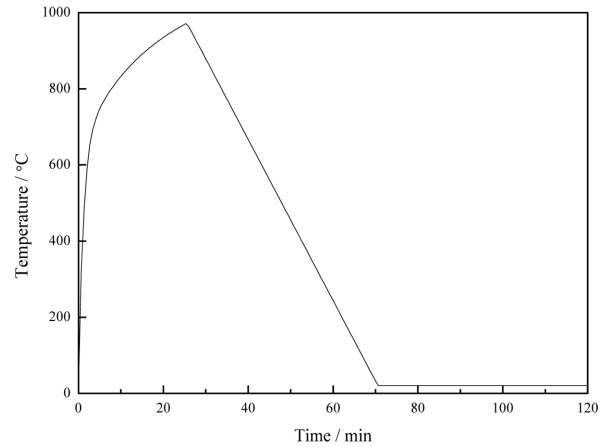


Figure 6. The chosen parametric fire.

explosion or earthquake, or that the structure is still under construction.

Two dimensional heat transfer analyses are performed for the composite sections using the fire imposed boundary conditions specified in Section 2.2.1. The recently developed fire and heat transfer modules in OpenSees are used for the temperature predictions (Usmani et al., 2010). The temperature-dependent thermal properties of the concrete (with moisture content of 1.5%) and the slab are specified according to (EN1993-1-2, 2005). The top surface of the concrete slab is assumed to be exposed to an ambient temperature of 20 degrees. The surface convective heat transfer coefficient and the emissivity are 25 kW/m² and 0.7 respectively. A contour plot of temperature distribution at 1000 s in the composite section is shown in Fig. 7. The temperature distribution in the beam is relatively uniform except for the values in the top flange which are around 200 degrees lower than those at other locations due to heat sink effect of the adjacent concrete slab. Large temperature gradients are developed through the depth of the concrete slab owing to its low heat conductivity.

The column is assumed to be fully protected with 2 cm sprayed-on mineral fibre. One side of the section is exposed to ambient at 20 degrees, while the other three sides

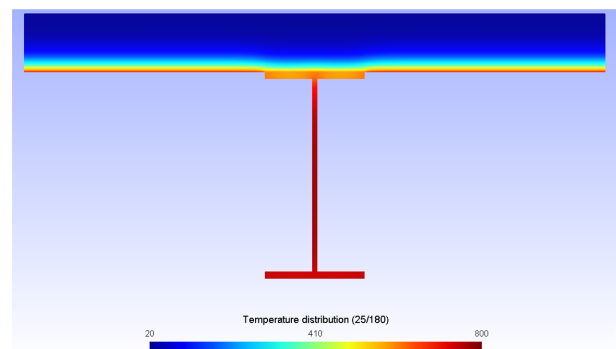


Figure 7. Temperature distribution in the composite section at 1000 s.

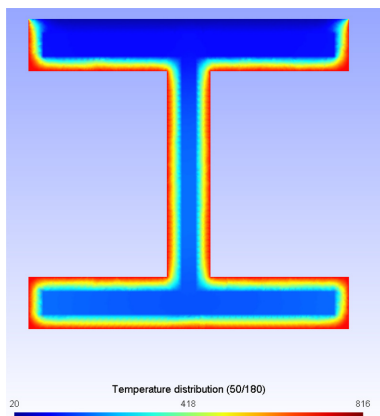


Figure 8. Temperature in the protected column section at 2000 s.

are exposed to the fire environment. Thermal properties of the protection material are 300 kg/m^3 for density, 0.12 W/mK for heat conductivity, 1200 J/kg K for specific heat (Franssen et al., 2009). The surface convective heat transfer coefficient is 25 kW/m^2 and the emissivity is 0.7. As shown in Fig. 8, the temperature rise in the column is no greater than 400 degrees until 2000 s when the fire temperature reaches its peak values. For simplicity, the columns were considered to be heated uniformly in the subsequent structural modelling based on the results of the heat transfer analysis.

3. Weak Floor and Strong Floor Collapse Mechanisms

Previous research by Usmani et al. (2009) has investigated the behaviour of tall buildings in fire and demonstrated that two distinctive collapse mechanisms can be identified, namely the ‘weak floor’ and ‘strong floor’ mechanisms. A previous parametric study performed by the authors has established some criteria on the appearance of these mechanisms and has shown that for most cases the strong floor collapse is more likely (if collapse occurs) for typical composite tall buildings and weak floor collapse occurred mainly for beams that were deliberately under-designed or when there were simultaneously burning fires on a large number of floors (typically greater than three, also a relatively unlikely occurrence). However, this type of collapse mechanism should may become probable in other forms of construction (for example when floors are supported by long span and light weight trusses or cellular beams, which are quite popular in modern tall buildings).

The established criteria are based on the behaviour of the “bottom pivot floor” (the floor immediately below the lowest fire floor), which for all the cases in this paper is the 5th floor. If the bottom pivot floor reaches its plastic moment capacity at midspan (from $P-\delta$ moments induced because of having to provide a reaction to the “pull in”

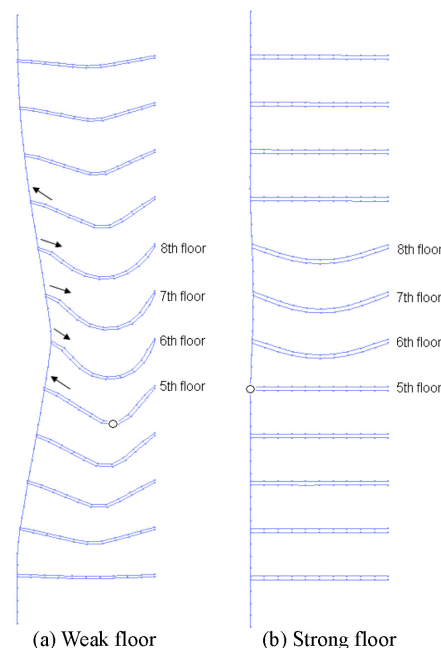


Figure 9. Deformed shapes of weak floor and strong floor failures.

forces at the fire floors, see Fig. 9(a)), a hinge is formed (Fig. 9(a)) in the floor and the weak floor mechanism is initiated. The bending failure spreads to the lower adjacent floor and then further downwards (with potentially a similar failure spreading upwards from the top pivot floor) leading to a progressive and disproportionate collapse of the structure. If the bottom pivot floor is able to sustain the increasing bending moments, the column connecting the pivot floor may reach its plastic moment capacity first (as indicated by the hinge shown in Fig. 9(b)) at a section near the floor-column connection which then initiates the strong floor failure. A three hinge mechanism forms with two further hinges in upper floors. The key distinction between the two collapse mechanisms is the initiation. In

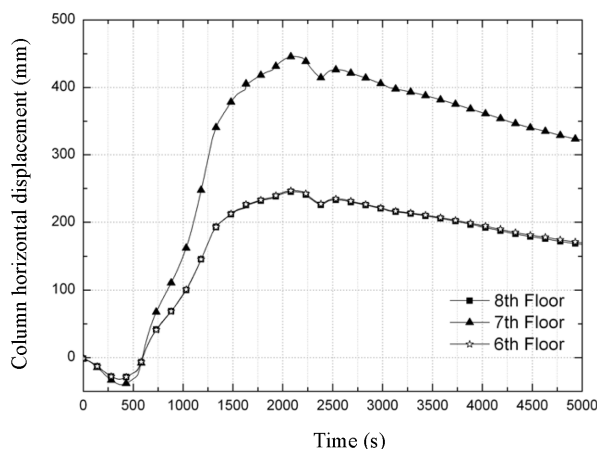


Figure 10. Column horizontal displacement for strong floor collapse.

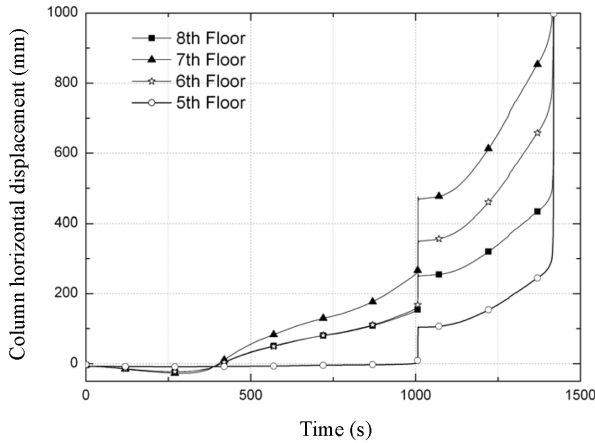


Figure 11. Column horizontal displacement for weak floor collapse.

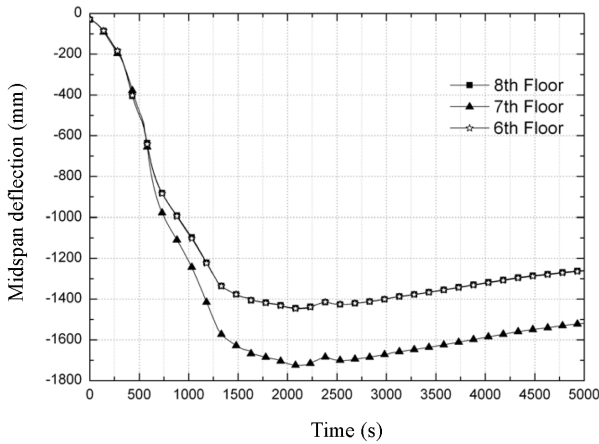


Figure 12. Midspan deflection for strong floor collapse.

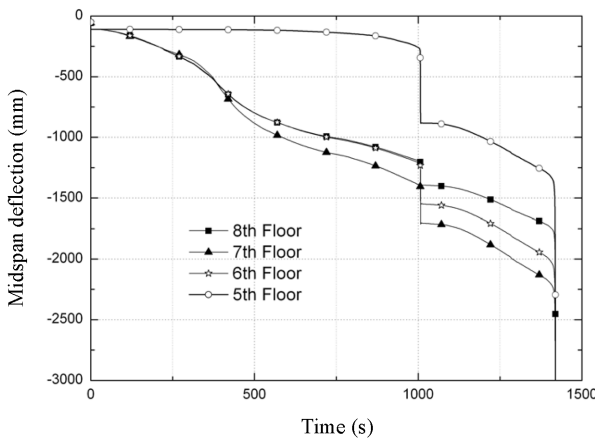


Figure 13. Midspan deflection for weak floor collapse.

the weak floor mechanism collapse initiates due to bending failure of the bottom pivot floor itself, while in the strong floor mechanism collapse initiates due to combined compression and bending failure of the column adjacent

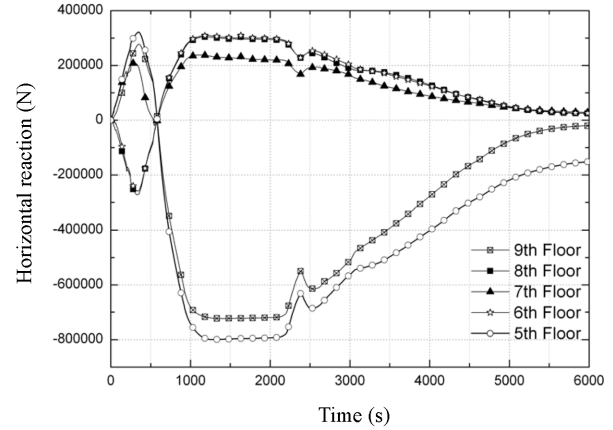


Figure 14. Membrane forces for strong floor collapse.

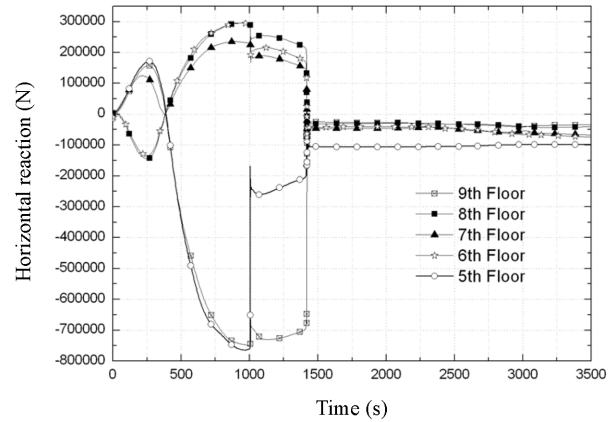


Figure 15. Membrane forces for weak floor collapse.

to the bottom pivot floor. Figure 9 shows deformed shapes for weak and strong floor collapse under a three floor fire scenario (fire affected floors are floors 6 to 8).

These mechanisms have been demonstrated in the past but a short introduction to them will be given in this paper, in order to examine later how these mechanisms are affected by vertically travelling fire scenarios. Figures 10 and 11 show the horizontal displacements of the column at the level of the fire floors (with negative direction denoting outward movement and positive denoting inward movement) for the strong floor and the weak floor mechanisms respectively. In addition, Figs. 12 and 13 plot the midspan displacement of the fire floors and the bottom pivot floor for the strong and weak floor collapse respectively. It can be seen that the bottom pivot floor (i.e., the 5th floor) experiences significant deflections while in the strong floor collapse only the fire floors displace extensively. This indicates bending failure of the bottom pivot floor which does not occur in strong floor collapse and hence is a main distinguishing characteristic of weak floor collapse. Figures 14 and 15 plot the horizontal reaction forces at the rigid end restraints for the strong and weak floor collapse respectively. These reactions repre-

sent the membrane forces in the floors. It can be seen that initially for the strong floor collapse, the bottom and top pivot floor (5th and 9th floors) as well as the middle fire floor (7th floor) are in tension and snap into compression

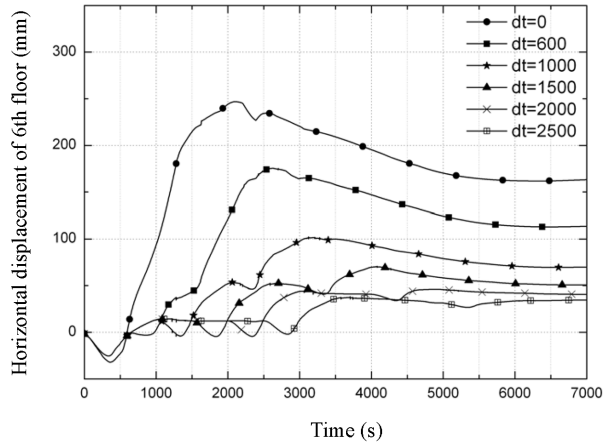


Figure 16. Horizontal displacement of the 6th floor.

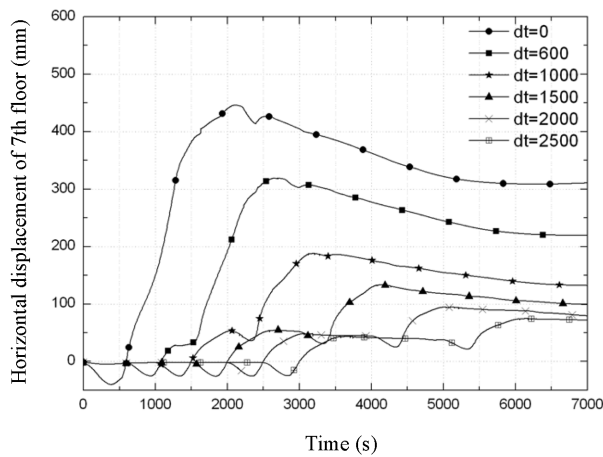


Figure 17. Horizontal displacement of the 7th floor.

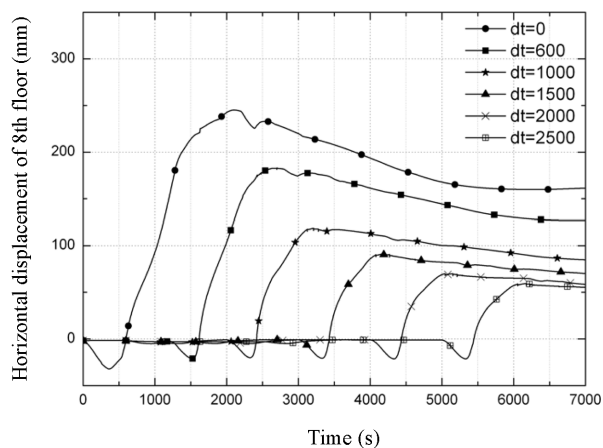


Figure 18. Horizontal displacement of the 8th floor.

when the pull-in process starts. On the other hand the bottom and top fire floors (6th and 8th floors) are in compression initially and later snap into tension when the pulling-in of the columns initiates. For the weak floor case, the overall behaviour of the membrane forces are similar but it can be clearly seen that the bottom and top pivot floor (5th and 9th floor) buckle suddenly in this case.

4. Collapse Mechanisms under Vertically Travelling Fires

The following sections are report the findings of our investigation of the aforementioned collapse mechanisms in vertically travelling fires. A parametric study was performed to examine this, by analysing the previous models with a series of different vertical propagation rates of fire.

4.1. Strong floor mechanism

Figures 16~18 plot the column horizontal displacements over time for the 6th, 7th and 8th floors respectively (i.e., the heated floors). The comparison for all the cases demonstrates that as the time delay of the travelling fires

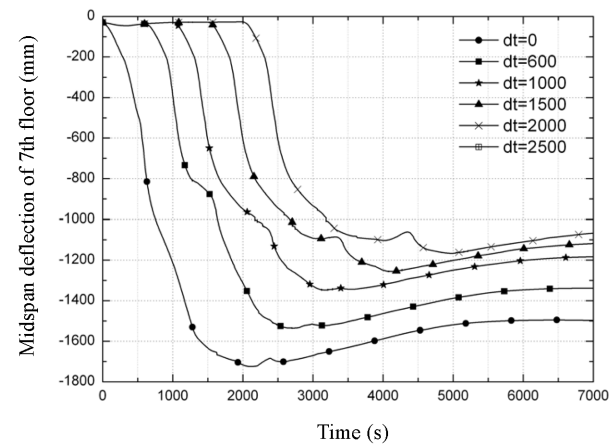


Figure 19. Midspan deflection of the 7th floor.

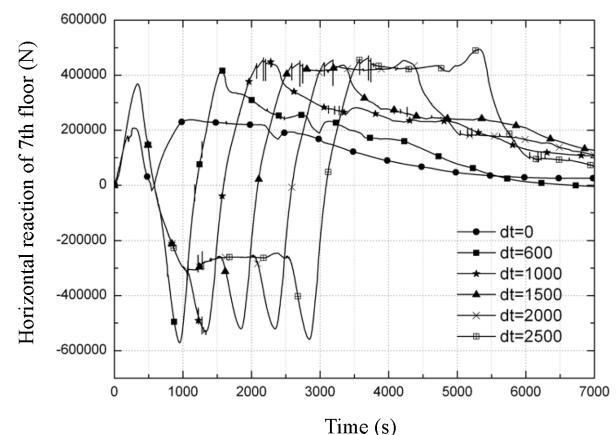


Figure 20. Membrane force of the 7th floor.

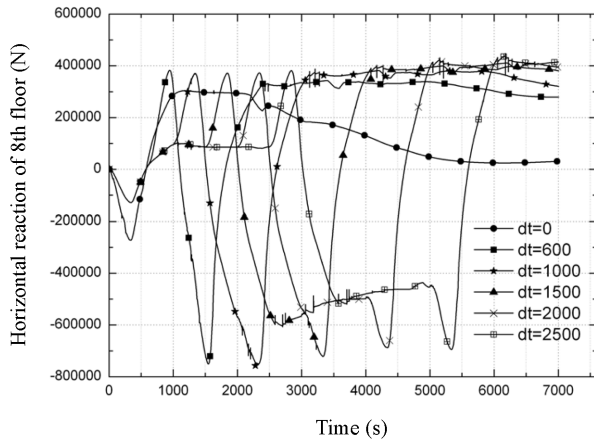


Figure 21. Membrane force of the 8th floor.

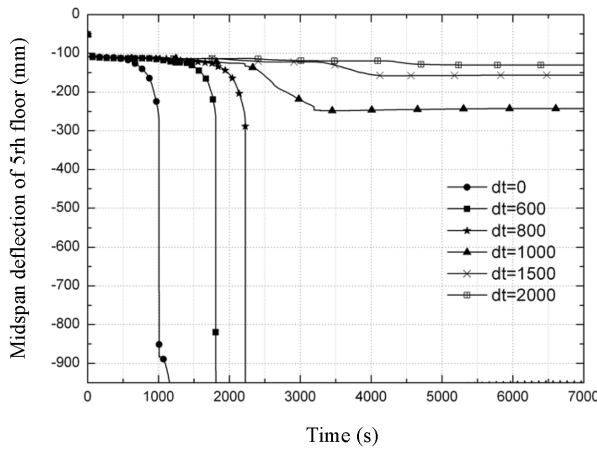


Figure 22. Midspan deflection of the 5th floor.

increases the maximum positive column horizontal displacement decreases. Moreover the displacements increase substantially only when all the three floors are on fire. It can also be noticed that the maximum negative displacement (thermal expansion phase) for the 6th floor, which is the first to heat, is similar for all cases independent of the time delay unlike the 7th and 8th floors which heat later and the maximum displacement reached is similar for all the travelling fires but lower than the simultaneous fires.

Figure 19 plots the midspan deflection of the 7th floor (middle fire floor). It can be seen that as the travelling speed decreases, the maximum midspan deflection obtained also decreases (from approximately $L/5$ for $dt = 0$, to $L/9$ for $dt = 2500$).

Figures 20 and 21 plot the variation of membranes forces in the 7th and 8th floor for different travelling speeds. It can be seen that as the time delay of travelling fires increases the maximum tensile force also increases. The maximum compressive forces are also much higher than those in the simultaneous fires case. It should however be noted that the variation of both the maximum tensile and compressive forces is not large between different

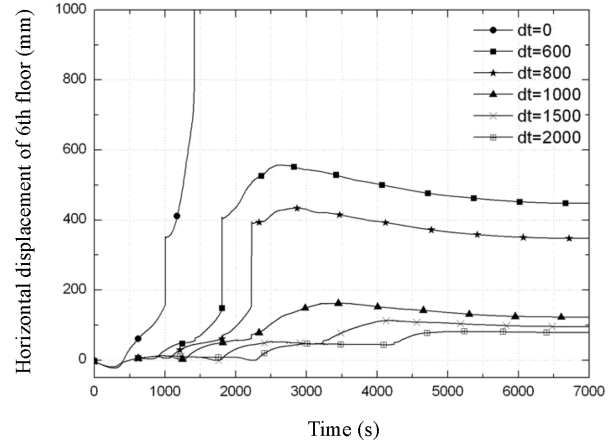


Figure 23. Horizontal displacement of the 6th floor.

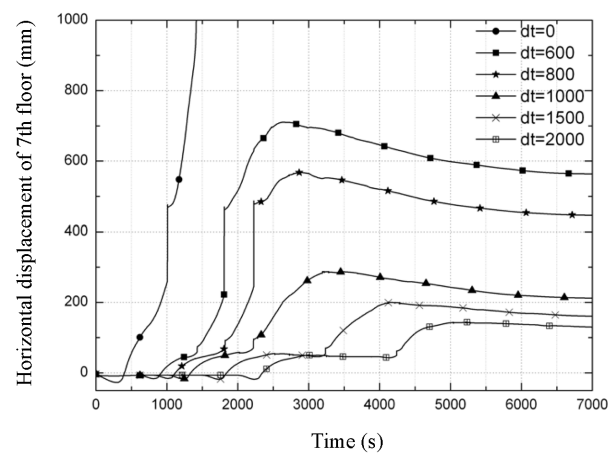


Figure 24. Horizontal displacement of the 7th floor.

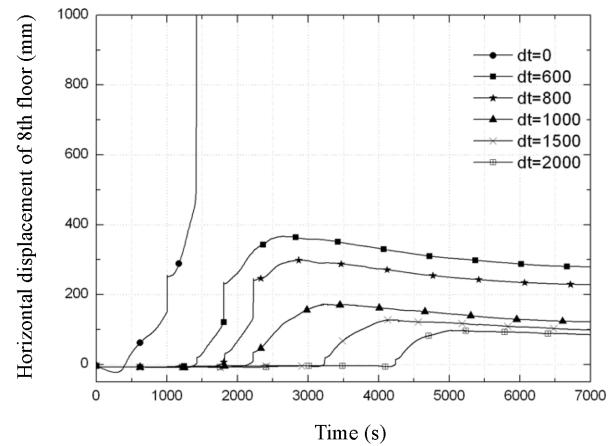


Figure 25. Horizontal displacement of the 8th floor.

travelling fires.

4.2. Weak floor mechanism

Figure 22 plots the midspan deflection of the 5th floor

for a weak floor collapse mechanism. It can be seen that for rapid rates of spread (600, 800) the floor fails while for slower rates of spread the floors does not fail and hence weak floor collapse does not occur but strong floor collapse could. The parametric studies showed other cases where weak floor collapse still occurs irrespective of the time delay. Figures 23 to 25 plot the horizontal displacements of the column for the 6th to 8th floor respectively and demonstrate that the column pulls in less as the travelling speed decreases.

Figures 26 and 27 plot the membranes forces of the 7th and 8th floor for different travelling rates for the weak floor collapse case. The observed differences in terms of maximum tensile force reached are similar to the strong floor case in that as dt (i.e., time delay) increases the maximum tensile force also increases.

5. Application of Vertical Traveling Fires to the WTC Towers

It would be interesting to examine the effect of travelling fires on an actual tall building that collapsed due to fire such as the WTC towers. Even after a decade since

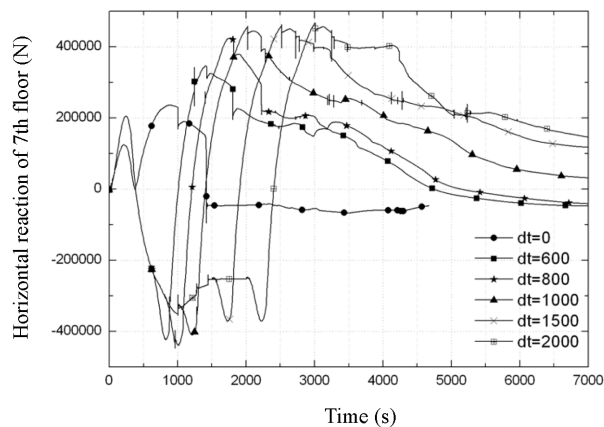


Figure 26. Membrane force of the 7th floor.

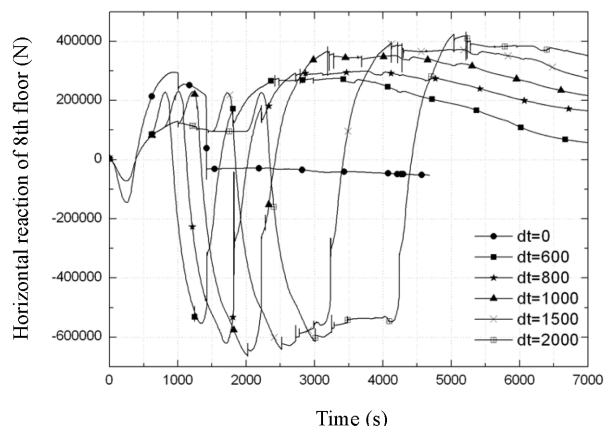


Figure 27. Membrane force of the 8th floor.

this event it seems that there are still lessons to be learned from this high profile failure. This section will discuss whether simultaneous fires assumed in previous studies were conservative and how the tower may have responded under vertically travelling fires.

Forensic investigation on the collapse of WTC towers was performed initially by FEMA and later by the National Institute for Standards and Technology. Other smaller scale independent research studies were carried out by Quintiere et al. (2002), Usmani et al. (2003). Quintiere et al. studied the response of the tower's composite floor at elevated temperatures but did not present a clearly defined collapse mechanism. On the other hand, Usmani et al. and the NIST report presented a consistent global collapse mechanism where the perimeter columns were pulled in due to the large deflections in the floors. NIST demonstrated that this collapse mechanism was in accordance with the visually observed evidence. Usmani et al. examined the vulnerabilities of the particular structural form under fire conditions without taking into account any aircraft damage while NIST carried out a coupled analysis in order to reproduce the sequence of events. This work followed the approach used by Usmani et al., that is, the structure was intact before the onset of the fire and the impact of aircraft damage was neglected.

5.1. Structural details

The two towers were almost identical, 110 stories tall, and were equipped with an innovative light truss floor system. In the models presented in this paper, a two dimensional slice of the half of the building is modelled from the 90th to the 101st floor. The dimensions of the truss system and the rigid core are taken from the FEMA

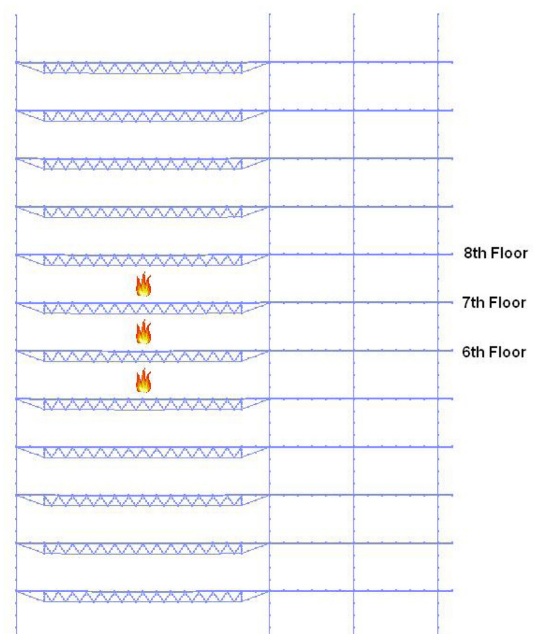


Figure 28. Finite element model of the WTC Towers.

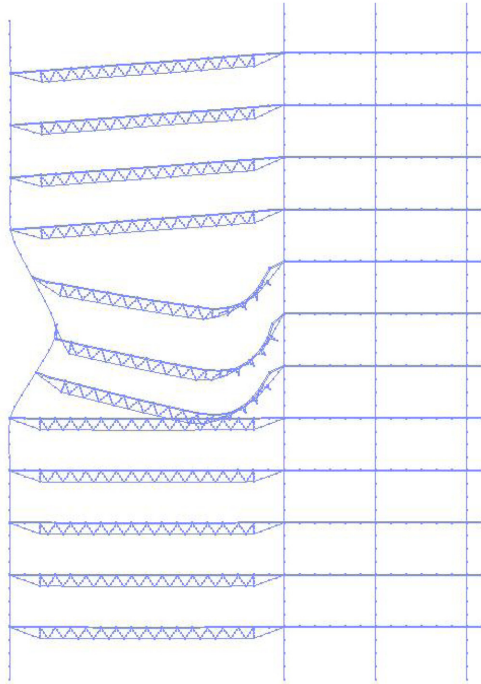


Figure 29. Deformed shape for simultaneous fires.

report. The fire is assumed to occur in the outer area of the 5th to 7th floors and thus affecting floors 6 to 8 as seen in Fig. 28.

5.2. Modelling results

The WTC towers were modelled under a three floor travelling fire, varying the rate of travel to investigate this phenomenon in the context of a real failure. A range of values were used, similar to the earlier study on more generic tall buildings.

The deformed shape for the 3-floor simultaneous fire scenario is demonstrated in Fig. 29. Similarly the deformed shapes for Δt of 1000 and 2500 can be seen in Figs. 30 and 31.

Figures 32 to 34 plot the horizontal displacement of the 6th, 7th and 8th floors. It can be seen that the strong floor instability occurs in all scenarios with varying travelling speeds examined. A clear difference in the expansion phase can be seen between the simultaneous and the travelling fire cases. For all the travelling fire cases, global instability occurs when the fire begins to heat a third floor (subsequent to the first two), i.e., the 8th floor in this paper.

Figures 35 and 36 also plot the axial forces on the first and last element of the top chord of the truss system. The figures indicate that the members experience increased tension as the travelling time delay increases but also compression which for the travelling fires cases is significantly higher than the simultaneous one.

The results of the study indicate that the WTC tower models show collapse even for slow travelling fires and that the same collapse mechanism as shown in previous

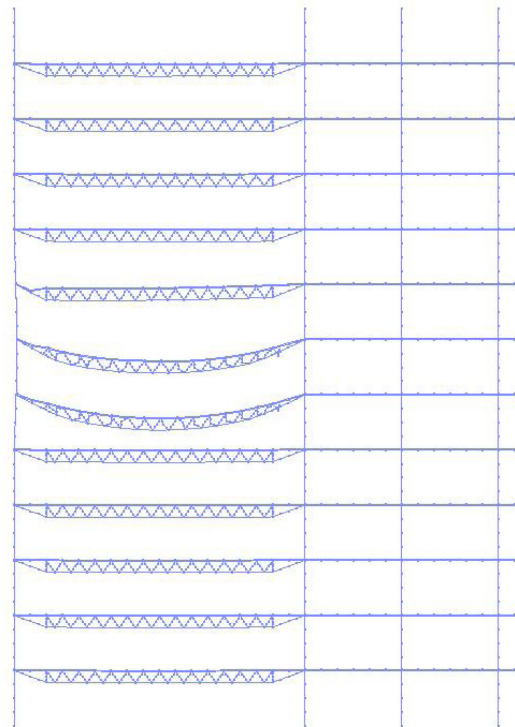


Figure 30. Deformed shape for travelling fires with a 1000 sec time delay.

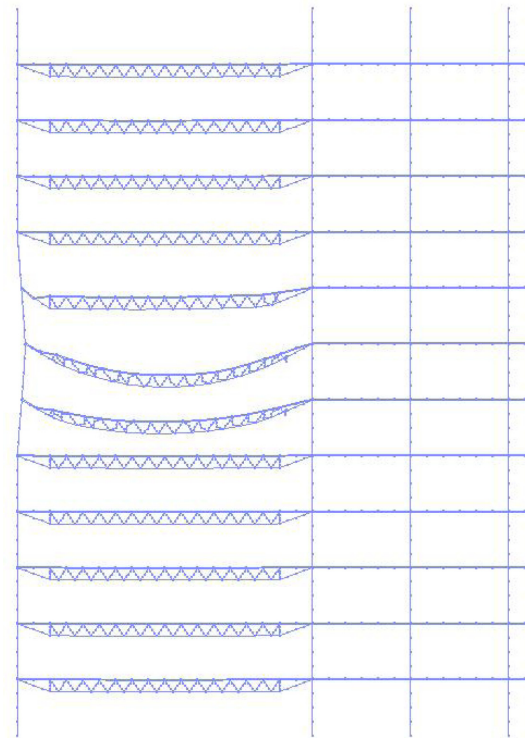


Figure 31. Deformed shape for travelling fires with a 2500 sec time delay.

research still applies. This suggests that vertical compartmentation could probably delay but not avoid collapse if

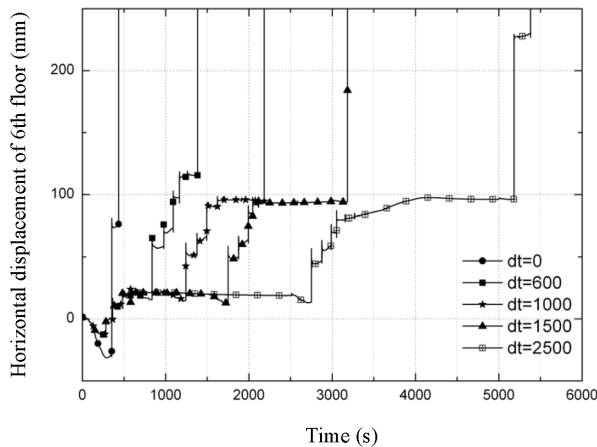


Figure 32. Horizontal displacement of the 6th floor.

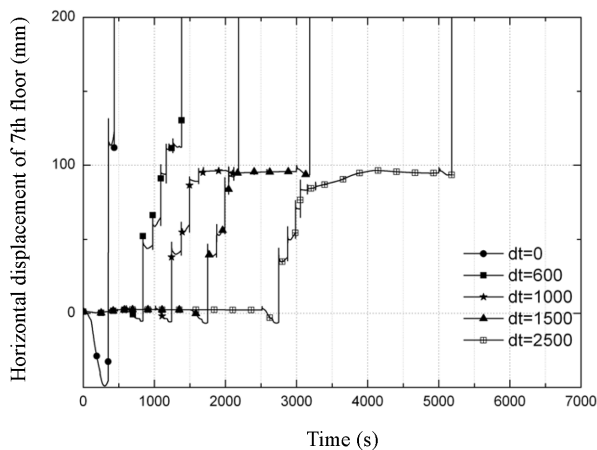


Figure 33. Horizontal displacement of the 7th floor.

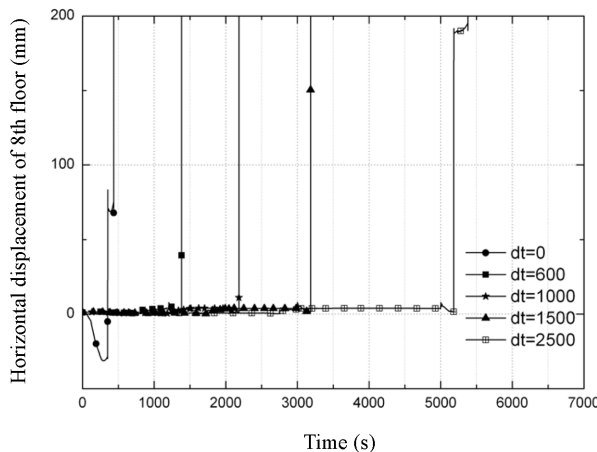


Figure 34. Horizontal displacement of the 8th floor.

a 3-floor fire scenario occurred (there are many caveats to this of course, not least the validity of the model, and the highly unpredictable nature of travelling fires themselves).

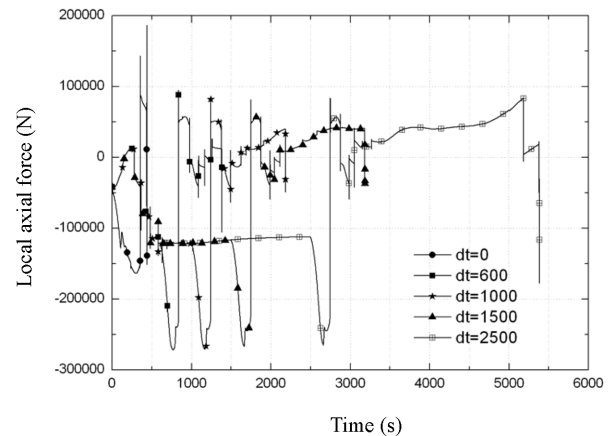


Figure 35. Local axial force of 1st element in top chord of the 7th floor.

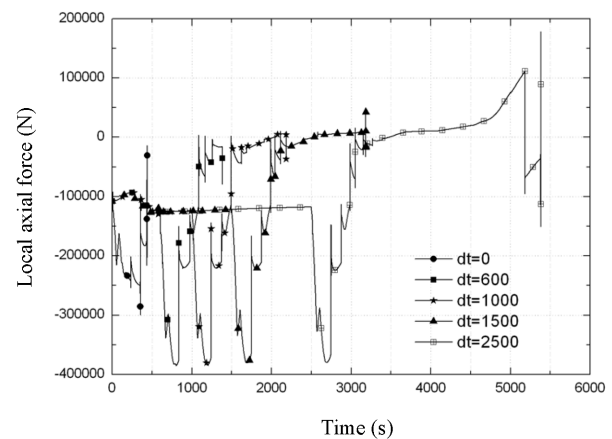


Figure 36. Local axial force of last element in top chord of the 7th floor.

6. Discussion and Summary of Key Findings

6.1. Discussion of the results

Multifloor fires can cause collapse, and designers will need to include this scenario when designing tall buildings in fire, but there is no guidance on the number of floors in fire and the travelling rate of the fires between the floors. This paper investigated the effects of vertically travelling fires on the collapse mechanism of tall buildings with the aim of providing guidance to designers when using multiple floor fire scenarios as part of their design.

The results of the study demonstrate that travelling fires have beneficial impact in terms of the global structural response of composite tall buildings in comparison to simultaneous fires. This is because the steel members of the composite frame have time to cool down and thus regain strength and stiffness. This suggests that a simultaneous multiple floor fire could provide an upper bound scenario when designing composite tall buildings against fire induced collapse. This will be of interest to designers

wishing to investigate the performance of tall building in a multiple floor fire since it is practically impossible to predict the actual time (or rate) needed for a fire to travel vertically since it depends on many factors as discussed in Section 2.2.1.

Contrary to the beneficial effect of the travelling fires in terms of the global structural response, it was noticed that significantly higher tensile forces were also present in the floors compared to the case of simultaneous multiple floor fires. This was also observed in the study of Roben et al. (2010) and can result in possible connection failure in case the connections do not have the adequate tensile capacity to withstand these higher tensile forces. Although more research is needed on this issue, it was observed that the variation in the maximum tensile force reached for the different travelling rates is small. This is important information for designers, as it is difficult to consider all possible travelling rates.

The results of this study also highlighted the importance of vertical fire compartmentation on the behaviour and possible collapse of tall buildings. Restricting fire from travelling to another floor would decrease substantially the possibility of collapse (since the collapse mechanisms discussed are less likely to occur in single floor fires). However, it is recognised that this cannot be achieved easily in practise and hence the use of thermally-resistant window assemblies and horizontal projections (SFPE, 2012) should reduce the speed of vertical spread reducing the risk of collapse or at least delaying it in order for evacuation and emergency response to occur safely.

Simultaneous multiple floor fires can be considered as a simpler and conservative upper bound scenario for design against collapse in multiple floor fires. However, a scenario where a slow travelling fire should also be examined to ensure that the tensile capacity of connections is not underestimated. More research will be required for defining an appropriate travelling rate.

In this work, the detailed vertical fire spread process was not explicitly addressed, instead a time delay was used as a lumped parameter to study the consequence of vertically travelling fires. Fires travelling horizontally across the floor are also not included. The models presented in this paper were based on the assumption that post-flashover fires developed for each floor and a uniform temperature distribution is assumed in the whole compartment. It is recognised that this may not be valid for structures of very large floor areas or long column heights (characteristics that are common in modern infrastructure) where in reality fire is not burning uniformly and simultaneously on each floor. Further research is currently undergoing in applying a horizontally travelling methodology to tall buildings by the authors (Jiang et al., 2012).

6.2. Summary of key findings

- Vertical fire compartmentation is very important in

securing structural integrity and allowing time for people to evacuate safely

- Simultaneous multiple floor fires have been found to be more conservative than vertically travelling fires in terms of global structural behaviour

- A strong floor collapse is less probable for slower travelling rates

- A weak floor collapse in a simultaneous or rapidly travelling fire may become strong floor collapse for a slow travelling fire

- A suitable number of floors simultaneously burning at the same time can be used as a conservative upper bound for global behaviour by designers

- Travelling fires are seen to produce higher tensile axial forces in the floors and thus the potential of connection failure is increased

- Suggested values for travelling times cannot be defined as these depend on multiple parameters specific to a building or structure, and thus cannot be generally applicable

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